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MODERN STUDY OF THE ATOM

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REALITY OF ATOMS AND MOLECULES

IN the latter part of the last century many distinguished men of science still doubted that reality underlay the atomic and kinetic theories and therefore preferred to deal with chemical phenomena mainly from the standpoint of energy changes. Chief among these prophets of the energetic school was Wilhelm Ostwald. After working over the material for the new edition of his "Outlines of General Chemistry," however, Ostwald wrote in 1908: "I am now convinced that we have recently become possessed of experimental evidence of the discrete or grained structure of matter, which the atomic hypothesis sought in vain for hundreds and thousands of years. The isolation and counting of gas ions, on the one hand, which have crowned with success the long and brilliant researches of J. J. Thomson, and, on the other, the agreement of the Brownian movements with the requirements of the kinetic hypothesis, established by many investigators and most conclusively by J. Perrin, justify the most cautious scientist in now speaking of the experimental proof of the atomic structure of matter." When, therefore, even the foremost protagonist of the energetic school has come into the ranks of the atomists, there can now be little doubt that the evidence points to the reality of atoms and molecules, at least in the minds of those who are competent to judge. It may be added that much new evidence has accumulated since Ostwald wrote in 1908. We may, therefore, consider that the ground has been cleared of that type of obstructor who denies the existence of atoms other than as figments of the imagination.

In what follows I wish to present, for the benefit chiefly of those who have not had opportunity to follow the literature of the subject, a picture of the atom as we envisage it to-day. To do this most briefly, one can not in everything follow the historical development of the last thirty years. It is quicker, and often clearer, to give results first with supporting evidence afterwards, to employ a deductive as well as an inductive method.

The Present-day Atom

Let me, therefore, say at once, and, for brevity, in a very didactic manner, that atoms are built up of two and only two kinds of building materials, bricks, or units of construction, namely protons and electrons. Under like conditions, all protons are alike and all electrons are alike. The chief attributes of these protons and electrons may be simply tabulated thus:

	MASS (AT REST)	ELECTRIC CHARGE	DIAMETER IN CM.
Electron	1/1845	—1	3.8×10^{-13}
Proton	1	+1	2×10^{-16}

The hydrogen atom consists of one proton and one electron. The unit of mass here employed is a mass 1/1846th part less than that of the hydrogen atom itself. The precise value of this mass in grams does not here interest us any more than does the precise value of the unit electric charge expressed in terms of the conventional electrostatic units.

Every atom consists of a positively charged nucleus in which is concentrated nearly all the mass of the atom, and this nucleus is surrounded by a number of electrons sufficient to neutralize the nuclear charge. The atom as a whole is, of course, electrically neutral. For hydrogen, the positive nucleus consists of but one proton; but, in all other atoms, the positive nucleus contains what are called intranuclear electrons as well as protons. The value of the net positive charge on the nucleus of any particular type of atom is equal to the atomic number of the atom, that is, the ordinal number the atom would receive if all our 92 elements were numbered in order of increasing atomic weight, or, better, because of the three standard disorderly cases of potassium-argon, nickel-cobalt and iodine-tellurium, in order of rank in the periodic tabulation of the elements. The roll of the chemical elements, as we shall see, was called first, if incompletely, by one Moseley in 1914, and, of the 92 now on the roll, five elements are yet absent. The number of extranuclear or planetary electrons in chemical atoms, therefore, runs from 1 for hydrogen, 2 for helium, 3 for lithium, etc., up to 92 for uranium, the heaviest atom not yet extinct. The number of planetary electrons is the same as the atomic number of the atom.

The outside diameter of atoms is of the order of 1 to 5×10^{-8} cm., or 100,000 times the diameter of the electron, so that it is evident that the spacing of the nucleus and extranuclear electrons in an atom is a very open one, more so than in our solar system, in which, also, our central sun is inordinately large for true relative dimensions. So far as the volumes of the discrete structural units, protons and electrons, are concerned, therefore, atoms are filled chiefly with emptiness or void. Granting that the planetary electrons are so few in number, never over 92, and so light in weight, it is obvious that, as has been said, the main mass of the atom must be concentrated in its nucleus. To illustrate the make-up of an atomic nucleus, consider, for example, the case of the atom of fluorine. Its atomic weight is about 19. Therefore its nucleus must contain 19 protons, which would furnish a positive charge of +19. But its atomic number is 9, and hence its nuclear charge is +9. To reduce a positive charge of 19 to 9 will require the presence of 10 electrons in the nucleus, ten negative units of electrostatic charge thus offsetting ten of the positive units.

As regards the picture of the atom developed so far, there is much unanimity. The kind of questions not yet solved are those about the detailed constitution of the nucleus, and the arrangement of the extranuclear electrons. Further study might therefore be divided into (1) study of the nucleus and its constitution, and (2) study of the extranuclear portion of the atom and its possible arrangements of electrons, with the orbits or oscillations in which they are engaged. But we shall not follow this program.

Having placed before you a broad idea of the present-day conception of the structure of atoms, I wish now to go back and look at some of the methods of study that have led to the knowledge we have gained.

ELECTRONS AND PROTONS

Our knowledge of the electron has been reached chiefly through a study of the discharge of electricity through gases, with which the name of Sir J. J. Thomson is so closely associated. We should not forget, however, that, as early as the seventies of last century, Sir William Crookes observed streamers of light emerging from the cathode of highly evacuated discharge tubes. These he considered were composed of matter in a new, fourth state which he called "radiant matter." Certain German investigators thought the streamers were due rather to an ether wave motion analogous to light. It was not till 1895 that Sir J. J. Thomson showed that Crookes had been correct. The cathode rays are now known to consist of streams of swiftly moving electrons. Like any other particles that carry a charge, these electrons are deflected from a straight line course by either a magnetic or an electrostatic field properly applied, and, by using known field strengths of both kinds and measuring the resulting deflections of the electrons, the relation e/m between their charge and their mass can be ascertained. This is a method of measurement of very fundamental importance. Very high speed electrons of different, definite speeds are ejected by certain "radioactive" atoms at the moment when such atoms break up, and a study of e/m for these electrons has shown that, if the charge is the same, the apparent mass increases with the measured speed of the electrons in a manner that harmonizes precisely with what would be anticipated on theoretical grounds if their mass were entirely what is called electromagnetic, or entirely due to their charge. Knowing that the mass of an electron is entirely electromagnetic in origin, we can then, assuming a spherical form, calculate by electromagnetic rules its radius, which comes out with the value noted above.

Individual electrons have been isolated by Millikan and others, and their charge evaluated precisely in electrostatic units. No electric charge that was a fractional part of that of an electron was ever encountered in this work, but only whole number multiples of it. From this it appears that negative electricity comes in small unit amounts or grains, like pepper. In other words, negative electricity, like matter, is atomic. At present we know less about the proton, or unit positive charge, than about the electron; its much greater mass, if electromagnetic, gives it a correspondingly smaller radius, as noted above, because, for the same charge on a spherical surface, electromagnetic mass varies inversely as the radius of the sphere.

Origin of X-Rays

The electrons in a discharge tube, such as an X-ray bulb, can be made to move with very high speeds, and so to carry much energy. They are stopped abruptly by striking the atoms that constitute the target in the bulb, and, by transferring some of their own energy, stimulate radiation of short wave light on the part of certain of the extranuclear electrons belonging to these atoms. They likewise themselves emit general wave radiation as they slow down. The very existence of these so-called X-rays, emerging from such targets, was not observed until 1896, and they were not known to consist merely of short wave length light until 1912.

X-Rays and Crystal Structure

I may remind you that one of the most successful methods of studying and analyzing common light is by means of a Rowland diffraction grating, which consists of a large number of fine lines ruled exceedingly closely together on a transparent or else reflecting surface. Such a grating will perform its analytical function only provided the ruling or grating space is sufficiently close compared with the wave length of the light being tested. A picket fence is a possible Rowland grating, but is far too coarse to give useful results. So likewise a real Rowland grating is far too coarse to give appreciable diffraction of X-rays, because these are of such short wave length. In 1912 it occurred to the Swiss Laue that in ordinary crystalline substances we have ready-made very minutely spaced diffraction gratings, of skeletal type, indeed, and in three instead of only two dimensions of space. Stated otherwise, he thought the atoms of which the crystal is built might furnish centers to diffract the X-ray light, and these atoms are already arranged by Nature in rank, file and column with perfect regularity and with the requisite close spacing. Laue's expectations were brilliantly fulfilled, and the method has been developed by the Braggs in England, by Dr. Hull at Schenectady and by many others.

Because it is based on a relationship between the spacing of the layers of atoms and the wave length of the light diffracted by them, this powerful modern method of analysis may be employed in either of two ways, namely, to study (a) either the light wave length or (b) the spacing of the atoms. A single relationship connects these two unknowns. To get a value to start from, the atomic spacing in, say, sodium chloride can be computed from the known number and plausible crystallographic arrangement of atoms in one cubic centimeter of crystalline salt. Hence we can find the wave length of some particular easily-generated monochromatic X-ray light, which we can thenceforth use conveniently as our yard-stick in measuring atomic spacings in other crystals.

RESULTS FROM THE X-RAY SPECTROMETER

(a). Moseley in 1914 tried many different elements as targets in the X-ray bulb, analyzed the resulting X-rays by means of a crystal, and found that each element emitted general X-radiation, but also its own characteristic sets of X-rays of but a few kinds, that is, each element emitted a characteristic X-ray spectrum, consisting of but a few spectral lines peculiar to the element. Selecting a particular type of emitted light (K, L, etc., series) for making comparisons amongst the elements, Moseley arrived at the remarkable result that the square roots of the wave frequencies varied in progressive stepwise fashion from element to element, giving a series of equal whole-number steps that would, if complete, run approximately from 1 for hydrogen to 92 for uranium, just as the atomic numbers do. Any missing step was conspicuous, and indicated clearly an element lacking. From this we have learned that we must search for just five new elements, and that we must adjust our atomic numbers to allow for the elements that are missing.

It may here be remarked that the ordinary old style light spectra emitted by the chemical elements in the flame, arc, spark, sun or stars are of much more complex character than these simpler X-ray spectra. The latter give us information in regard to those extranuclear electrons which, after suffering displacement, gain positions of stability nearest to the nucleus; while the former longer wave light spectra inform us of the relatively slower radiations of those electrons that reach stations of stability in the outer regions of the atom. Within the last few years, both types of spectra have been so extended as to overlap, and the former outstanding gap of four octaves of light frequency has been completely bridged.

(b). The distances apart of layers of atoms in crystals are of an order smaller than one millionth of an inch. Small as are these distances, however, they are measurable by the X-ray spectrometer with an accuracy much better than one hundredth of one per cent. Given the crystallographic data of a crystal and its atomic arrangement, one may, by assuming the atomic weights of the constituent atoms, determine the density of the crystal by X-ray analysis with an accuracy superior to that of the more usual older methods. Conversely, if the density of the crystal is known, but the atomic weight of one of the constituent atoms is unknown, this may similarly be determined. Of greater interest, however, is the employment of the X-ray spectrometer to determine the arrangement of the atoms in a crystal. This can be done with a good deal of assurance for crystals belonging to the crystallographic systems of higher symmetry. Simple substances, such as the pure metals, usually crystallize in such systems, and have been subjects of fruitful study. Especially interesting to the organic chemist is the crystal lattice of diamond, in which each carbon atom is surrounded by four others at equal distances from it and in the directions of the four corners of a tetrahedron from its center of gravity. It has heretofore been tacitly assumed that the nuclei of the atoms in the crystal acted as simple point centers for diffracting light; but closer study reveals evidence of the position of certain extranuclear electrons which are in all probability those that constitute the valence bonds of the carbon. It is further apparent that these valence electrons, if not stationary, at least patrol stations other than the nucleus. This is confirmatory of the Lewis-Langmuir theory of atomic structure, to be mentioned shortly. Of even greater interest to the organic chemist are the recent studies by means of the X-ray spectrometer of the possible arrangement of the atoms in naphthalene, anthracene and allied substances. Viewed from one standpoint, the carbon atoms in diamond lie at the corners of hexagons bent at their corners so as to fit on puckered surfaces, or surfaces composed of V-like corrugations like galvanized roofing without rounded bends. In spite of its different crystalline form, very different hardness, etc., graphite, the other crystalline form of carbon, exhibits an identical arrangement of carbon atoms in puckered hexagonal formation, but with the planes containing the hexagons further apart. Assumption of this same corrugated hexagonal structure, which appears so favorable for carbon atoms, satisfies the experimental results obtained with crystals of naphthalene in the X-ray spectrometer. One can not say that the organic chemist's customary graphic formula for naphthalene and its allies has been independently proved correct; but it has at least been shown that this time-honored formula is in complete harmony with the new experimental facts.

Arrangement of Extranuclear Electrons in Atoms

Passing from the arrangement of atoms in molecules to the arrangement of the extranuclear or planetary electrons in individual atoms, we reach a field where the experimental facts, chemical or spectroscopic, are more difficult of present interpretation, and where, at present, we are largely being guided and, I should add, stimulated by hypothesis. The hypothesis at present most acceptable to the chemist, doubtless because it was designed to fit the chemical rather than the spectroscopic facts, is that of Lewis and Langmuir; and this may be most easily visualized by the aid of models of atoms. Here we have the electrons patrolling definitely localized stations which are arranged in concentric shells round the nucleus. Similarity in number and arrangement of stations in the outermost shell makes for similarity of chemical properties, and so accounts for the well-known family resemblances of a chemical kind among the atoms. Furthermore, for many of the commoner atoms at least, the number of electrons in the outermost shell that gives the greatest stability is, on this "octet" theory, eight. If we personified such atoms, their chief ideal in life would be to secure, by hook or crook, an outside shell of precisely eight electrons; and this ideal motivates all the chemical reactions of such atoms. The two possible mechanisms by which the octet ideal is achieved are by reciprocal lending and borrowing or else by sharing electrons, corresponding to the conceptions of electrovalence and covalence, respectively. Atoms that already have eight electrons in their outer shells, like neon and argon, have no motive for any chemical action, and, as is well known, are entirely inert. By these new conceptions of valence, certain molecular structures are anticipated to be closely similar (isosteric) which would be entirely dissimilar according to the older ideas of valence; and the close similarity of crystal form (isomorphism) actually observed in many such cases, a stumbling block and even a reproach to the chemical crystallographers of but ten years ago, strongly confirms the correctness of the newer views in these instances.

Less interested in the chemistry of the atoms, Bohr and his followers have been more concerned in devising an atomic model that will explain the kinds of energy radiated by an atom as light when one of its extranuclear electrons falls from a location of higher to one of lower potential energy, this light having a frequency which depends not on the final environment reached by the electron but rather on the energy made available by the fall. This theory is brilliantly successful, but hitherto only in the two simplest cases. If the planetary electrons all revolve in simple ellipses round the nucleus, there is insufficient localization of fields of force around the atom to satisfy the valence demands of the chemist, even although the orbits be not in the same plane. To me, the possibility of twisted or looped orbits round the nucleus would offer more satisfaction; as also would a complex electron to account for the facts of radiation.

Because both these types of hypothesis as to the arrangement and activities of the extranuclear electrons are at present in a somewhat speculative stage, I prefer to pass on to tell of other matters closer to the facts reached by the modern methods of study.

SPONTANEOUS DISINTEGRATION OF ATOMS: ISOTOPES

All of our atoms of atomic weight over 206 are observed to have the proclivity to disintegrate. The nucleus of the atom of Uranium-1, for example, has a mass about 238 and a charge of +92. Occasionally, such an atomic nucleus, for cause utterly unknown, suffers a cataclysm in which the nucleus of a helium atom is expelled with enormous speed. (A helium atom consists of a minute nucleus built of 4 protons bound together by 2 electrons, which is surrounded by two planetary electrons). This expelled portion, endowed with terrific energy of motion, is called an alpha-particle. Because it lacks the two planetary electrons of the helium atom, it bears a double positive charge, and the moving alpha-particle can therefore be studied in the magnetic and electrostatic fields and the ratio measured of its charge to its mass, by which measurement its nature was divulged. On picking up two planetary electrons the alpha-particle becomes a helium atom. The precise volume has been measured of helium gas generated in this wise from radioactive material ejecting alpha-particles in numbers that can be counted one by one, and so has been enumerated directly the number of helium atoms per cubic centimeter of the helium gas collected.

After throwing out its alpha-particle, the residual portion of the Uranium-1 atom, having lost 4 protons, possesses a mass 234 instead of 238. It has lost from its nucleus also 2 electrons, and therefore a net charge of (4—2) or +2. Its atomic number is thus smaller by 2, that is 90, and its ordinal position in the periodic table is two places below and to the left of Uranium-1. It is, in fact, a new element, named Uranium-X_1, which resembles the element Thorium. But it is a short-lived element, and soon expels from its nucleus an electron, or beta-particle, yielding a residual product, called Uranium-X_2, of the same atomic weight 234, but of atomic number 91. This disrupts with loss of another beta- particle even sooner than the last, producing the atom of an element, called Uranium-2, of atomic weight still 234, but of atomic number 92. But 92 is the atomic number of Uranium-1 from which we started. Thus Uranium-1 and Uranium-2 have the same nuclear charge, +92, and must have the same arrangement of extranuclear electrons, for this is ordered by the nuclear charge, and not appreciably by the nuclear mass. Thus, the outsides of U-1 and U-2 will be identical, and on the outside of an atom do its chemical properties depend. Consequently, U-1 and U-2, falling in the same ordinal position in the periodic system, are identical chemically and therefore inseparable by chemical means. Such elements are called isotopes. They have the same nuclear charge. Elements with the same nuclear mass are called isobars, as U-X_1, U-X_2, and U-2.

After a chain of successive disintegrations involving losses of 8 and 6 alpha-particles (mass 4) respectively, both uranium (mass 238) and thorium (mass 232) produce atoms with the nuclear charge of lead. On account of their different parentage, however, these two types of lead atoms would be expected to have masses of 206 and 208 respectively. They have each been isolated, from uranium and thorium minerals respectively, and found to possess atomic masses closely as expected.

Most of the known radioactive or spontaneously disintegrating elements have atomic weights of 206 or over. But rubidium and potassium are also radioactive, as are one of the constituents of common brass and also the metal platinum, although these latter atomic species disintegrate at an exceedingly slow speed and emit alpha-particles so lacking in energy that they are difficult to detect. There is no reason why the habit of disintegration should not be general among elements. In any case, we are clear that isotopic atoms, whether formed in a process of disintegration or in a process of evolution, should be identical chemically, and so, like birds of a feather, should be found together. The question then arises, how many of our elements are mixtures of isotopes, indistinguishable by chemical difference? The question can be answered only by physical methods. If the isotopes are heterobaric, of different mass, then they can be identified and separated because of their difference in mass. Speed of diffusion or of free evaporation depends on mass, and so the elements mercury and chlorine have both been shown to consist of mixtures of heterobaric isotopes.

The Mass Spectrograph

But the most fertile method yet employed to recognize heterobaric isotopes is that devised by Sir J. J. Thomson, depending on the fundamental fact, already mentioned above, that different values of the ratio charge to mass of a charged particle moving in a high vacuum will give rise to different degrees of deflection in the magnetic and electrostatic fields. A gas or vapor particle containing the element under investigation is therefore given a positive charge in the discharge tube, and its resulting deflection is studied. Such a particle may acquire more than one unit charge, but such multiple charges cause no confusion. Refinement of this beautiful method in the hands chiefly of Aston has shown us that the elements Li, B, Ne, Mg, Si, Cl, A, K, Ca, Ni, Zn, Br, Kr, Rb, Sn, Xe, Hg, are all, at least as we have them ordinarily available on this planet, mixtures of isotopes; whereas H, He, Be, C, N, O, F, Na, P, As, I, and Cs have been studied and proved simple. Published results on no others are yet available. Only those elements which can readily be obtained in stable gaseous form have yet been investigated; but as soon as any of the less volatile elements or their compounds are obtained in suitable gas form, additional results of interest will be forthcoming. Because his measurements in the mass spectrograph of the masses of most atoms had an accuracy of 0.1 per cent., Aston was enabled to discover that the atomic weights of the chemical elements investigated, save hydrogen, are invariably whole numbers on the scale oxygen=16, to the degree of accuracy mentioned. The fractional value 35.46 found by chemical analysis for chlorine, for example, is explained by that element's consisting of certain proportions of two isotopes of masses 35.0 and 37.0 respectively. Thus is the century old hypothesis of Prout, that all atoms have masses that are whole number multiples of the mass of the hydrogen atom, resurrected and rehabilitated, but with a unit of mass almost 0.8 per cent. less than that of the hydrogen atom. Mathematical rigor in this "whole number rule" is, however, not to be expected for a reason that will now be referred to.

A New Possible Source of Cosmical Energy

Hydrogen, in Aston's mass spectrograph, appears to have an atomic mass of 1.008 (0=16), precisely as found by the chemists. Hydrogen, however, is unique among the elements in having no electrons but merely one proton in its nucleus. In all other atomic nuclei there are electrons packed close to the protons, and this close packing of charges of opposite sign is expected, by electrical theory, to influence the electromagnetic mass of the complex by an amount dependent on the closeness of packing. If we could build a helium atom from the materials which are correctly furnished by four hydrogen atoms, there would ensue a loss of mass of about 0.8 per cent., since the atomic weight of helium is 4.00. This mass, however, can not be destroyed, but must appear, according to the relativity theory, as an equivalent amount of energy. The quantity of energy concerned in the transformation of 1 gram of hydrogen to helium, namely 8 milligrams, or about the weight of one fifth of a postage stamp, corresponds to what, as electrical energy at ten cents per kilowatt hour, would cost $20,000.

If such a synthesis of helium from hydrogen may be supposed to be going on in the sun, we have a much needed explanation of the sun's present brightness at his known old age.

Experimental Utilizations of Alpha-particles in Investigation

The alpha-particles expelled from radioactive elements are by far the most energetic entities with which we are yet acquainted. The swifter kinds have, for unit mass, an energy of motion 400 million times greater than that of a rifle bullet. Being helium nuclei without circumambient planetary electrons, they are very small, and readily shoot through atoms, knocking out their extranuclear electrons right and left. The damaged atoms soon pick up other electrons to fill the gaps, and thus suffer no permanent change. Alpha-particles pass through thin glass, leaving no hole. Very occasionally, an alpha-particle will make a bullseye collision with the nucleus of an atom. The consequence of this collision, in the case of nuclei of some light atoms, is that the nucleus struck is disintegrated, with the expulsion of a single, swift-moving proton. The experiment succeeds in the case of B, N, F, Na, Al, and P nuclei. In the case of aluminium, Rutherford found that the single protons expelled have an energy of motion that is 40 per cent. greater than that of the alpha-particle missile that struck the atom. What remains of the aluminium nucleus is still under investigation, but it is permanently changed and is certainly no longer aluminium. Thus, in transmuting an element, we obtain free energy. The alchemists expressed this allegorically when they identified the philosopher's stone, which would transmute metals, with the elixir of life, a source of ever fresh life or energy. Our enthusiasm for this transmutation is duly restrained by the knowledge that only about two per million alpha-particles make bullseyes on the aluminium nuclei.

In the case of the heavier atoms with their more highly charged nuclei, the alpha-particle, of the speed hitherto at our disposal, apparently loses too much energy in the approach to be able to effect disintegration of the nucleus. Its path is sometimes bent back in a large angle deflection, by an elaborate study of which in the case of gold the existence of the minute, positively charged nucleus of atoms was first established. The nuclear charges of gold, platinum, silver and copper have each been directly evaluated by this method, and agree with the atomic numbers of these atoms to 1 per cent., the known value of the experimental error.

The Duration and Possible Repetitions of Geological Time

The unchanging and, so far as all experiment goes, unchangeable spontaneous disintegration of heavy atomic nuclei has geological interests both in view of the time periods involved and also of the energy emitted in the process. Thorium disintegrates into thorium-lead, which is stable, at a rate which we have been able to ascertain. The ''range'' or distance travelled through matter by the expelled alpha-particles is strictly related to the rate of the various disintegrations, and such ranges and rates have ever remained constant for thorium and its descendants as evidenced by the constancy of the diameters of the range ''halos'' surrounding microscopic thorium inclusions in rocks of various ages. The diameters of these halos agree, also, with the ranges in air of the alpha-particles as studied to-day, and so the thorium clock has ever run at the same rate. Some thorium minerals contain lead whose measured atomic weight shows that it has practically all been derived from the decay of thorium atoms. From the ratio of the number of thorium atoms remaining to the number of those originally present, many of which are now represented by lead atoms which they produced, one can compute the age of the mineral, which thus gives a date to early paleozoic times of 150 million years back. Similar calculation from uranium minerals gives a period over 900 million years, but there is reason to believe that the uranium clock formerly ran fast, or, rather, that it appeared to run fast owing to the former presence of a third isotope of uranium, now almost extinct, of speedier rate of decay than what to-day we call U-1.

Rock analysis shows that, assuming percentage composition similar to that on the surface, there is enough radioactive material in a depth of only 12 miles of the earth's crust to supply by its daily disintegration all the heat the earth radiates daily into space. If an appreciable amount of radioactive material exists below this depth, as seems certain, then heat must slowly be accumulating within the earth's non-conducting crust. Eventually, therefore, if no compensating heat-absorbing process is taking place within, an unstable state will be reached when the underlying incandescent material will perforce evert itself to the exterior and there disburden itself of its accumulated heat by radiation into space at a very rapid rate proportional to the fourth power of the temperature. This is the earth's incandescent epoch. When the crust has cooled down again sufficiently, a new geological epoch of perhaps 200 million years may begin, to be followed in turn by another incandescent epoch, and so on, alternately, but more and more slowly, until the radioactive materials, if not regenerated, have by disintegration lost their available energy. This alternation the Brahmans have symbolized in their cosmogony as the indrawing and outbreathing of the breath of Brahma.